Atchison, David A. (2009) *Age-related paraxial schematic emmetropic eyes.* Ophthalmic & Physiological Optics : The Journal Of The British College Of Ophthalmic Opticians (Optometrists), 29(1). pp. 58-64.

Age-related paraxial schematic emmetropic eyes

David A. Atchison

School of Optometry & Institute of Health and Biomedical Innovation, Queensland University of Technology, 60 Musk Avenue, Kelvin Grove Q 4059

Correspondence to David A. Atchison, tel: +61 73138 6152, e-mail d.atchison@qut.edu.au

Abstract

Based on recent biometric data, I developed 4-surface paraxial schematic emmetropic eyes for different ages. There are three sets of schematic eyes: male, female and overall. With increase in age, the changes in the schematic eyes are decreased anterior chamber depth, increased lens thickness, decreased vitreous length, increased axial length, decreased anterior lens radius of curvature and increased lens equivalent refractive index. Gender differences are greater anterior corneal radii of curvature (0.07 mm), longer vitreous chambers (0.70 mm), longer axial lengths (0.70 mm) and lower lens equivalent refractive indices of male eyes (0.007) relative to female eyes. Gaussian parameters of the various schematic eyes are given.

Keywords: ageing, emmetropia, gender, refractive index, schematic eyes

Introduction

Listing proposed a schematic eye having a single surface cornea and a homogeneous lens in 1851 (Helmholtz, 1909). This type of model is known as a simplified eye. Since then, many schematic eyes have been developed at different levels of sophistication from the single spherical refractive surface models (reduced schematic eyes) to more recent custom models intended to have the characteristics of individual eyes including estimation of higher-order aberrations (Navarro *et al.*, 2006; Tabernero *et al.*, 2007). Many of the well known schematic eyes such as Gullstrand's No. 1 eye, Le Grand's full theoretical eye, Gullstrand-Emsley eye models are for relaxed emmetropic eyes or for eyes with small refractive errors (Atchison and Smith, 2000). Variants on these have been used with refractive errors, eg Atchison (2006) for myopic eyes, and with accommodation (Navarro *et al.*, 1985).

The optics of the eye change with age. While the lens changes, particular the gradient index, have been modelled with age eg (Atchison and Smith, 1995; Diaz, 2008; Goncharov and Dainty, 2007; Navarro *et al.*, 2007a; Navarro *et al.*, 2007b; Smith and Atchison, 1997; Smith *et al.*, 1992; Smith *et al.*, 2008; Smith *et al.*, 1991), there have been few age related schematic eyes. Rabbetts (2007) provided an elderly eye with a homogeneous lens, which when compared with the Bennett-Rabbetts relaxed eye, including a refraction of +1.0D to reflect the trend towards hypermetropia in later life, decreased lenticular radii of curvature, decreased anterior chamber depth by 0.65 mm, increased lenticular thickness by 0.75mm, decreased vitreous chamber depth by 0.1mm, and reduced equivalent refractive index by -0.016. Atchison and Smith (Atchison and Smith, 2000) developed a four surface age-dependent, relaxed, emmetropic, paraxial eye based on some earlier work (Smith et al., 1992). This had decreasing anterior chamber depth and compensating lens thickness, decreasing lens radii of curvature and decreasing equivalent refractive index with age A in years of

$$n_L = 1.4608 - 0.000488A - 0.00000097A^2 \quad (1)$$

which was noted to be very high compared with the refractive index of the lenses of other schematic eyes.

Atchison *et al*. (2008) completed an optical and biometric study of approximately 106 healthy emmetropic eyes of largely Caucasian subjects between the ages of 18 and 69 years (Atchison *et al*., 2008). This gives an opportunity to update models of paraxial schematic eyes parameters. As there were equal numbers of male and female subjects with similar age distributions, this gives also the opportunity to explore gender differences in eye models.

Method and Results

Details of the techniques and results can be found in Atchison *et al*. (2008). Subjects were carefully screened to have corrected visual acuities of 6/6 or better, Pelli-Robson contrast sensitivities were ≥1.65 for subjects aged 18-39 yrs and ≥1.50 for older subjects, pass a Humphrey FDT C-20-1 visual field screening test, and have normal results with a desaturated D15 test. They had Grade 1 or better for nuclear, cortical and posterior subcapsular cataract, and Grade 2 or better for age-related maculopathy (AREDS, 2001a, 2001b). One eye was tested for each participant having non-cycloplegic spherical equivalent within the range -0.88 D to +0.75 D and with ≤ 0.50 D astigmatism. Right eyes were used unless outside the criteria.

A variety of instruments was used. More than one instrument was used for some tests and not all subjects took part in all tests. Parameters for the schematic eyes are based on Medmont E-300 videokeratoscope (anterior corneal radius of curvature and anterior surface asphericity), Pentacam Scheimpflug instrument (posterior cornea radius of curvature, central corneal thickness, anterior chamber depth), ultrasound (lens thickness, vitreous length), and a Purkinje imaging technique. The lens radii of curvature and the lens equivalent index were provided by the Purkinje image technique, combined with results from the other techniques (distances and corneal radii of curvature). Other parameters that were not measured or estimated are the refractive indices of the cornea, aqueous and vitreous which were taken to be those of the Gullstrand's No.1 schematic eye.

Table 1 provides parameters of the "non-gender", male, and female schematic eyes. The parameters are based on linear regression equations obtained for the various quantities, with constants (mean values) used where regressions for age were not significant (Atchison *et al.*, 2008). The stop is placed at the anterior lens vertices. Some parameters had gender differences where these had been found to be significant, and apart from vitreous length the differences were age-invariant. As discussed below, the vitreous and hence axial lengths were manipulated so that the schematic eyes were emmetropic to within ±0.1 D over the range of ages and genders. Tables 2 to 4 provide Gaussian properties of the non-gender, male, and female schematic eyes at various ages. Figure 1 compares the parameters and some properties of non-gender schematic eyes at ages of 20 years and 70 years, and Figure 2 compares the parameters and some properties of 20 year old male and female schematic eyes.

Non-gender schematic eyes

With increase in age, the lens thickness increases at about twice the rate that the anterior chamber depth decreases. Also the lens anterior surface radius of curvature decreases and the lens equivalent refractive index decreases. Using the parameters including the non-age dependent vitreous length of 15.92 mm (Atchison *et al.*, 2008) in a paraxial raytrace, all eyes were found to be slightly hypermetropic. It was thus necessary to increase the vitreous length V_L in an age dependent way, and the formula

$$VL \text{ (mm)} = 16.146 - 0.0028A \tag{2}$$

was adopted where A is the age in years. The vitreous length thus decreases in the schematic eyes by 0.14 mm over a 50 year age range, being 0.17mm and 0.03 mm longer than 15.92 mm at ages of 20 years and 70 years, respectively. Rather than the regression obtained by Atchison et al. (2008) for the axial length AL of

$$AL \text{ (mm)} = 22.984 + 0.0113A \tag{3}$$

the axial lengths of the schematic eyes are given by

$$AL \text{ (mm)} = 23.182 + 0.0102A \tag{4}$$

which increases the length by 0.17mm and 0.12 mm at ages of 20 years and 70 years, respectively.

The common paraxial schematic eyes have equivalent refractive indices of about 1.42, and that of my schematic eyes is higher at

$$n_L = 1.4506 - 0.00035A \tag{5}$$

This equations gives indices lower than that used in the previous model (Atchison and Smith, 2000) as given by equation (1) below 54 years, but the indices are higher for ages above 54 years.

With increase in age, there are changes in the cardinal points and pupils. Between the ages of 20 years to 70 years the principal points move towards the cornea by 0.12 mm, the nodal points move away from the cornea by 0.12 mm, the pupils move towards the cornea by 0.05 mm, and the size of the entrance pupil relative to the aperture stop reduces by 2%.

Male and Female Schematic Eyes

Compared with female schematic eyes, male schematic eyes have greater anterior corneal radii of curvature (by 0.07 mm), longer vitreous chambers (by 0.72 mm), longer axial lengths (by 0.72 mm) and lower lens equivalent refractive indices (by 0.007). Accompanying the differences in axial length, males have greater powers than females by 2.3 D. They also have less powerful corneas and lenses by 1.1 D and 1.6 D, respectively.

As for the non-gender eyes, the vitreous lengths of the gender were manipulated so that the eyes were close to being emmetropic. Rather than the differences between male and females being the experimental mean of 0.51 mm, I had to make the differences 0.72 mm, an increase of 0.20 mm. A consequence of this is that the axial lengths of male eyes are 0.72 mm longer than the female eyes rather than the experimentally determined 0.62 mm, an increase of 0.10 mm. This 0.10 mm represents a discrepancy between vitreous and axial length gender differences. The likely reason for this is that males have longer anterior chambers and possibly greater lens thicknesses, as reported in large scale studies (see Atchison et al. (2008)), but as these differences were not significant in this study the "slack" has to be taken up by vitreous differences.

The cardinal points and pupils of the male and female eyes change with age in a similar fashion as for the non-gender eyes. The principal points of male eyes are 0.06 mm closer to the cornea than those of female eyes, while the nodal points of male eyes are 0.15 mm further away from the cornea than those of female eyes. The differences in pupil positions and sizes between the genders are small.

Discussion

Based on a recent optical and biometric study (Atchison *et al.*, 2008), I have developed 4-surface schematic emmetropic eyes of adult eyes at different ages. There are non-gender specific schematic eyes as well as eyes for males and females. The notable features of the models are that they change in length with age and gender, are shorter than other 4-surface schematic eyes by up to 1.0 mm, and the equivalent refractive indices is higher than these other eyes by up to 0.03. Age dependent parameters are the anterior chamber depth, lens thickness, vitreous length, anterior lens surface radius of curvature and lens equivalent refractive index. Gender-dependent parameters are anterior corneal surface radius of curvature, lens equivalent refractive index and vitreous length.

The interesting age-related parameters for the schematic eyes are the well documented decrease in anterior lens surface radius of curvature, decrease in lens equivalent refractive index, and increase in axial length of approximately 0.50 mm across a 50 year interval. The reason for the last of these has been canvassed (Atchison *et al.*, 2008) – I do not suggest that the eye gets bigger with age, but because many young adult emmetropic eyes would become hypermetropic with age, the older ages consist of bigger eyes that have either remained emmetropic throughout adult life or may even have been slightly myopic in young adult life.

The schematic eyes can be used to predict the changing refraction with age of eyes that are emmetropic in early adulthood. Here I assume that the longitudinal data of an individual eye matches the cross-sectional data of the model except for the axial length remaining constant. I set the vitreous length to be

$$VL \text{ (mm)} = 16.350 - 0.0130A \quad (6)$$

to give the non-gender schematic eye's 20 year old axial length of 23.39 mm. The refraction changes by about 0.029 D/year with the 70 year old eye being 1.4 D hypermetropic (Figure 3). This change is considerably smaller than obtained in Saunders' cross-sectional and longitudinal studies (Saunders, 1981, 1986) and does not reveal that before the age of about 30 years, mean refraction is heading in the negative (myopic) direction before reversing direction (Figure 3). The data are in better agreement with an earlier study of Slataper (1950) who found a myopic shift up to about the age of 30 years, followed by a hypermetropic shift of about 1.1 D between 30 and 70 years. Other studies considering older populations have reported mean refraction changes between the 40s and 70s of about 0 D (Wickremasinghe *et al.*, 2004), 1.2 D (Shufelt *et al.*, 2005), and 2.0 D (Wojciechowski *et al.*, 2003; Wong *et al.*, 2001).

The axial lengths of the non-gender schematic eyes range from 23.4 mm at 20 years to 23.9 mm at 70 years. The Gullstrand-Emsley, Liou & Brennan, Navarro, Bennett & Rabbetts, Le Grand and Gullstrand No. 1 eyes have lengths ranging in order from 23.9 to 24.4 mm (Atchison and Smith, 2000), so generally these eyes are shorter than the common schematic eyes. This is reflected in the equivalent powers, with mine varying from 62.6 to 60.8D, as compared with 58.6 D to 60.5 D for the other schematic eyes. The reduced length of these schematic eyes is supported by recent large-scale population studies which obtained mean lengths ranging between 23.3 mm and 23.6 mm (Koretz *et al.*, 1989; Shufelt *et al.*, 2005; Wickremasinghe *et al.*, 2004; Wong *et al.*, 2001).

The gender difference in axial length of 0.75 mm of the schematic eyes is slightly higher than the 0.62 mm found in the Atchison et al. (2008) study and the studies mentioned above for which differences ranged from 0.47 mm to 0.65 mm.

As noted earlier, the lens equivalent refractive index of the schematic eyes for this study (equation (5)) are considerably higher than those of the common 4-surface eyes. Using Scheimpflug photography, Dubbelman *et al*. (2001) obtained values of

$$n_L = 1.441 - 0.00039A \qquad (7)$$

which are about 0.01 lower than given here. In addition, the estimate of lens back surface radius of curvature of -6.86 mm is flatter than other recent estimates of -5.9 mm (Dubbelman and Van der Heijde, 2001) and -6.1 mm (Koretz et al., 2004) using Scheimpflug photography and of -5.6 mm by a magnetic resonance imaging related technique (Koretz et al., 2004). This suggests that our lens equivalent index might be a little too high, combined with a slightly too flat posterior radius of curvature.

The schematic eye models have used equivalent refractive indices for the lens, rather than gradient indices as used in more sophisticated models of the lens eg (Atchison *et al.*, 2008; Liou and Brennan, 1997; Smith *et al.*, 1992). It must be said that the distribution adopted for these models has little experimental basis because of the paucity of refractive index data. Jones *et al.* (2005)'s *in vitro* magnetic resonance imaging study has confirmed that the indices in the middle and at the edge of the lens are relatively unaffected by ageing, but that the rate of change between these positions alters with ageing. They found the central index to be about 1.418 and the edge index to be about 1.371. With increase in age, the central plateau of constant refractive index becomes wider with a corresponding greater rate of change of refractive index towards the edge of the lens. These findings have been confirmed by the first reported *in vivo* measurements of the gradient index in two studies. Jones *et al*. (2007) found a non-age-dependent central refractive index of about 1.420, while Kasthurirangan *et al*. (2008) reported similar changes in distribution with increase in age as for the Jones *in vitro* study. Kasthurirangan *et al*. found smaller non-age-dependent gradient index extremes, 1.409 and 1.380, than those of the *in vitro* study. Their data were very noisy, and they attributed the smaller refractive index range partly to the averaging techniques they employed.

The refractive index of a homogeneous lens model must be higher than that of the central refractive index of gradient index models. As an example, in my earlier gradient index modelling of young eyes (Atchison, 2006) I included the Jones *et al*. (2005) limits in a parabolic distribution of refractive index; the equivalent constant index to get the same power would be 1.432. To match the age-related changes in index distribution described in the previous paragraph, the equivalent index must decrease, and this is incorporated in the presented models.

Shortcomings in the models developed here, such as the need to increase vitreous lengths beyond those found in the original experimental data, are likely to be related to the regression equations derived from the experimental data. All the regressions were linear and age-independent values were taken where the regressions were not significant. A larger population pool would have probably revealed more significant differences between genders and with age, and would have been expected to show that more sophisticated regressions than linear regressions were appropriate for some parameters.

Finally, there has been emphasis in recent years on customized models based on aberrations of the eye, but these are still of limited value as they optimize the unknown parameters such as lens surface asphericities and lens gradient index, with no confidence that these are anatomically correct. Individual eye models do not reveal the trends as reported in this paper.

Acknowledgment

Supported by NHMRC grant 290500.

References

AREDS. (2001a) The age-related eye disease study (AREDS) system for classifying cataracts from photographs: AREDS report no. 4. **131**, 167-175.

AREDS. (2001b) The age-related eye disease study system for classifying age-related macular degeneration from stereoscopic color fundus photographs: the age-related eye disease study report number 6. *Am. J. Ophthalmol.* **132**, 669-681.

Atchison, D. A. (2006) Optical models for human myopia. *Vis. Res.* **46**, 2236-2250.

Atchison, D. A., Markwell, E. L., Kasthurirangan, S., Pope, J. M., Smith, G. and Swann, P. G. (2008) Age related changes in optical and biometric characteristics of emmetropic eyes. *J. Vis.* **8**(4), 29, 1-20.

Atchison, D. A. and Smith, G. (1995) Continuous gradient index and shell models of the human lens. *Vis. Res.* **35**, 2529-2538.

Atchison, D. A. and Smith, G. (2000). *Optics of the human eye*. Oxford: Butterworth-Heinemann.

Diaz, J. A. (2008) ABCD matrix of the human lens gradient-index profile: applicability of the calculation methods. *Appl. Optics* **47**, 195-205.

Dubbelman, M. and Van der Heijde, G. L. (2001) The shape of the aging human lens: curvature, equivalent refractive index and the lens paradox. *Vis. Res.* **41**, 1867-1877.

Goncharov, A. V. and Dainty, C. (2007) Wide-field schematic eye models with gradient-index lens. *J. Opt. Soc. Am. A* **24**, 2157-2174.

Helmholtz, H. (1909). *Handbuch der Physiological Optik.* (Vol. 1): Optical Society of America.

Jones, C. E., Atchison, D. A., Meder, R. and Pope, J. M. (2005) Refractive index distribution and optical properties of the isolated human lens measured using magnetic resonance imaging (MRI). **45**, 2352-2366.

Jones, C. E., Atchison, D. A. and Pope, J. M. (2007) In-vivo measurement of crystalline lens diameter, thickness and central refractive index as a function of age and accommodation using MRI. *Optom. Vis. Sci.* **84**, 990-995.

Kasthurirangan, S., Markwell, E. L., Atchison, D. A. and Pope, J. M. (2008) In vivo study of changes in refractive index distribution in the human crystalline lens with age and accommodation. *Invest. Ophthalmol. Vis. Sci.* **49**, in press.

Koretz, J. E., Strenk, S. A., Strenk, L. M. and Semmlow, J. L. (2004) Scheimpflug and high-resolution magnetic resonance imaging of the anterior segment: a comparative study. *J. Opt. Soc. Am. A* **21**, 346-354.

Koretz, J. F., Kaufman, P. L., Neider, M. W. and Goeckner, P. A. (1989) Accommodation and presbyopia in the human eye — aging of the anterior segment. *Vis. Res.* **29**, 1685-1692.

Liou, H.-L. and Brennan, N. A. (1997) Anatomically accurate, finite model eye for optical modeling. *J. Opt. Soc. Am. A* **14**, 1684-1695.

Navarro, R., Gonzalez, L. and Hernandez-Matamoros, J. L. (2006) On the prediction of optical aberrations by personalized eye models. *Optom. Vis. Sci.* **83**, 371-381.

Navarro, R., Palos, F. and Gonzalez, L. (2007a) Adaptive model of the gradient index of the human lens. I. Formulation and model of aging ex vivo lenses. *J. Opt. Soc. Am. A* **24**, 2175-2185.

Navarro, R., Palos, F. and Gonzalez, L. M. (2007b) Adaptive model of the gradient index of the human lens. II. Optics of the accommodating aging lens. *J. Opt. Soc. Am. A* **24**, 2911-2920.

Navarro, R., Santamaría, J. and Bescós, J. (1985) Accommodation-dependent model of the human eye with aspherics. *J. Opt. Soc. Am. A* **2**, 1273-1281.

Rabbetts, R. B. (2007). *Bennett & Rabbetts' Clinical Visual Optics* (4th ed.). London: Butterworth-Heinemann.

Saunders, H. (1981) Age-dependence of human refractive errors. *Ophthal. Physiol. Optics* **1**, 159-174.

Saunders, H. (1986) A longitudinal study of the age-dependence of human ocular refraction. 1. Age-dependent changes in the equivalent sphere. *Ophthal. Physiol. Optics* **6**, 39-46.

Shufelt, C., Fraser-Bell, S., Ying-Lai, M., Torres, M. and Varma, R. (2005) Refractive error, ocular biometry, and lens opalescence in an adult population: the Los Angeles Latino Eye Study. *Invest. Ophthalmol. Vis. Sci.* **46**, 4450-4460.

Slataper, F. J. (1950) Age norms of refraction and vision. *Arch. Ophthalmol.* **43**, 466-481.

Smith, G. and Atchison, D. A. (1997) The gradient index and spherical aberration of the lens of the eye. *J. Opt. Soc. Am. A* **21**, 317-326.

Smith, G., Atchison, D. A. and Pierscionek, B. K. (1992) Modelling the power of the aging human eye. *J. Opt. Soc. Am. A* **9**, 2111-2117.

Smith, G., Bedggood, P., Ashman, R., Daaboul, M. and Metha, A. (2008) Exploring ocular aberrations with a schematic human eye model. *Optom. Vis. Sci.* **85**, 330-340.

Smith, G., Pierscionek, B. K. and Atchison, D. A. (1991) The optical modelling of the human lens. *Ophthalmic Physiol. Opt.* **11**, 359-369.

Tabernero, J., Benito, A., Alcon, E. and Artal, P. (2007) Mechanism of compensation of aberrations in the human eye. *J. Opt. Soc. Am. A* **24**, 3274-3283.

Wickremasinghe, S., Foster, P. J., Uranchimeg, D., Lee, P. S., Devereux, J. G., Alsbirk, P. H., Machin, D., Johnson, G. J. and Baasanhu, J. (2004) Ocular biometry and refraction in Mongolian adults. *Invest. Ophthalmol. Vis. Sci.* **45**, 776-783.

Wojciechowski, R., Congdon, N., Anninger, W. and Teo Broman, A. (2003) Age, gender, biometry, refractive error, and the anterior chamber angle among Alaskan Eskimos. *Ophthalmology* **110**, 365-375.

Wong, T. Y., Foster, P. J., Ng, T. P., Tielsch, J. M., Johnson, G. J. and Seah, S. K. (2001) Variations in ocular biometry in an adult Chinese population in Singapore: the Tanjong Pagar Survey. *Invest.Ophthalmol. Vis. Sci.* **42**, 73-80.

Table 1. Parameters of the schematic eyes as a function of age A in years. M, F: male and female eyes where their parameters are different

surface	medium	(equivalent) refractive index	radius of curvature (mm)	distance to next surface (mm)
	air	1.0		
1			7.75 M: 7.83 F: 7.66	
	cornea	1.376		0.54
2			6.5	
	aqueous	1.336		$3.369 - 0.0105A$
3			$12.283 - 0.0438A$	
	lens	$1.4506 - 0.00035A$ M: $1.4471 - 0.00035A$ F: $1.4541 - 0.00035A$		$3.1267 + 0.02351A$
4			-6.86	
	vitreous	1.336		$16.146 - 0.0028A$ M: $16.506 - 0.0028A$ F: $15.786 - 0.0028A$

Table 2. Gaussian properties of non-gender schematic eyes

parameter	20 years	30 years	40 years	50 years	60 years	70 years
anterior corneal surface power (D)	48.516	48.516	48.516	48.516	48.516	48.516
posterior corneal surface power (D)	-6.154	-6.154	-6.154	-6.154	-6.154	-6.154
equivalent power cornea (D)	42.479	42.479	42.479	42.479	42.479	42.479
anterior lens surface power (D)	9.433	9.490	9.553	9.621	9.694	9.775
posterior lens surface power (D)	15.685	15.175	14.665	14.155	13.644	13.134
equivalent power lens (D)	24.749	24.282	23.821	23.366	22.919	22.480
equivalent power eye (D)	62.611	62.226	61.850	61.483	61.126	60.782
anterior focal length f (mm)	-15.972	-16.070	-16.168	-16.265	-16.360	-16.452
posterior focal length f' (mm)	21.338	21.470	21.601	21.730	21.856	21.980
total length (mm)	23.386	23.488	23.590	23.692	23.794	23.897
retina to posterior focal point R’F’ (mm)	-0.002	0.008	0.014	0.015	0.011	0.001
refractive correction (D)	-0.004	0.024	0.040	0.043	0.030	0.003
anterior vertex to anterior focal point VF (mm)	-14.292	-14.411	-14.531	-14.651	-14.771	-14.891
anterior vertex to posterior focal point VF’ (mm)	23.384	23.496	23.604	23.707	23.805	23.899
anterior vertex to anterior principal point VP (mm)	1.679	1.659	1.637	1.614	1.588	1.561
anterior vertex to posterior principal point VP’ (mm)	2.046	2.026	2.003	1.978	1.949	1.918
anterior vertex to anterior nodal point VN (mm)	7.046	7.059	7.070	7.079	7.085	7.089
anterior vertex to posterior point VN’ (mm)	7.413	7.426	7.436	7.443	7.446	7.446
anterior vertex to entrance pupil VE (mm)	3.138	3.037	2.936	2.837	2.738	2.640
anterior vertex to exit pupil VE’ (mm)	3.832	3.721	3.610	3.498	3.384	3.271
entrance pupil size/aperture size M_{EA}	1.136	1.131	1.127	1.123	1.119	1.115
exit pupil size/aperture size $M_{E'A}$	1.041	1.042	1.043	1.044	1.045	1.046

Table 3. Gaussian properties of male schematic eyes

parameter	20 years	30 years	40 years	50 years	60 years	70 years
anterior corneal surface power (D)	48.020	48.020	48.020	48.020	48.020	48.020
posterior corneal surface power (D)	-6.154	-6.154	-6.154	-6.154	-6.154	-6.154
equivalent power cornea (D)	41.983	41.983	41.983	41.983	41.983	41.983
anterior lens surface power (D)	9.126	9.171	9.220	9.274	9.332	9.396
posterior lens surface power (D)	15.175	14.665	14.155	13.644	13.134	12.624
equivalent power lens (D)	23.955	23.477	23.005	22.537	22.076	21.622
equivalent power eye (D)	61.517	61.122	60.735	60.357	59.988	59.629
anterior focal length f (mm)	-16.256	-16.361	-16.465	-16.568	-16.670	-16.770
posterior focal length f ’ (mm)	21.718	21.858	21.997	22.135	22.271	22.405
total length (mm)	23.746	23.848	23.950	24.052	24.154	24.256
retina to posterior focal point R’F’ (mm)	-0.011	0.005	0.018	0.026	0.030	0.028
refractive correction (D)	-0.032	0.015	0.049	0.071	0.080	0.076
anterior vertex to anterior focal point VF (mm)	-14.602	-14.728	-14.855	-14.983	-15.111	-15.240
anterior vertex to posterior focal point VF’ (mm)	23.735	23.853	23.968	24.078	24.184	24.285
anterior vertex to anterior principal point VP (mm)	1.654	1.633	1.610	1.585	1.559	1.530
anterior vertex to posterior principal point VP’ (mm)	2.017	1.995	1.971	1.943	1.913	1.880
anterior vertex to anterior nodal point VN (mm)	7.116	7.130	7.142	7.152	7.160	7.165
anterior vertex to posterior point VN’ (mm)	7.479	7.493	7.503	7.510	7.514	7.515
anterior vertex to entrance pupil VE (mm)	3.133	3.032	2.932	2.833	2.734	2.637
anterior vertex to exit pupil VE’ (mm)	3.828	3.717	3.606	3.494	3.380	3.266
entrance pupil size/aperture size M_{EA}	1.134	1.130	1.126	1.121	1.117	1.113
exit pupil size/aperture size $M_{E'A}$	1.039	1.041	1.042	1.043	1.044	1.044

Table 4. Gaussian properties of female schematic eyes

parameter	20 years	30 years	40 years	50 years	60 years	70 years
anterior corneal surface power (D)	49.086	49.086	49.086	49.086	49.086	49.086
posterior corneal surface power (D)	-6.154	-6.154	-6.154	-6.154	-6.154	-6.154
equivalent power cornea (D)	43.051	43.051	43.051	43.051	43.051	43.051
anterior lens surface power (D)	9.740	9.809	9.885	9.967	10.057	10.155
posterior lens surface power (D)	16.195	15.685	15.175	14.665	14.155	13.644
equivalent power lens (D)	25.543	25.086	24.636	24.194	23.761	23.337
equivalent power eye (D)	63.769	63.393	63.027	62.671	62.327	61.997
anterior focal length *f* (mm)	-15.682	-15.775	-15.866	-15.956	-16.044	-16.130
posterior focal length *f* ’ (mm)	20.951	21.075	21.197	21.318	21.435	21.550
total length (mm)	23.026	23.128	23.230	23.332	23.434	23.536
retina to posterior focal point R’F’ (mm)	-0.003	0.000	-0.001	-0.007	-0.018	-0.036
refractive correction (D)	0.009	0.002	-0.002	-0.020	-0.054	-0.104
anterior vertex to anterior focal point VF (mm)	-13.980	-14.092	-14.205	-14.317	-14.429	-14.541
anterior vertex to posterior focal point VF’ (mm)	23.023	23.128	23.229	23.325	23.416	23.500
anterior vertex to anterior principal point VP (mm)	1.702	1.682	1.662	1.639	1.615	1.589
anterior vertex to posterior principal point VP’ (mm)	2.072	2.053	2.032	2.008	1.981	1.951
anterior vertex to anterior nodal point VN (mm)	6.971	6.983	6.993	7.001	7.006	7.009
anterior vertex to posterior point VN’ (mm)	7.341	7.354	7.076	7.369	7.372	7.370
anterior vertex to entrance pupil VE (mm)	3.143	3.042	2.941	2.841	2.742	2.644
anterior vertex to exit pupil VE’ (mm)	3.836	3.726	3.614	3.501	3.388	3.274
entrance pupil size/aperture size M_{EA}	1.138	1.133	1.129	1.125	1.120	1.116
exit pupil size/aperture size $M_{E'A}$	1.042	1.043	1.045	1.046	1.047	1.048

Figure Captions

Figure 1. Non-gender schematic eyes for ages of 20 years and 70 years, showing the cardinal point and pupil positions. Anterior focal points are not shown.

Figure 2. Male and female schematic eyes at 20 years, showing the cardinal point and pupil positions. Anterior focal points are not shown.

Figure 3. Refraction as a function of age for the non-gender schematic eyes when axial length does not change with age (vitreous length changes according to Equation (6)). For comparison, the cross-sectional and longitidunal data of Saunders are shown.